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Accelerating MRO procedures for composite materials using innovative detection techniques

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ABSTRACT

The development of large commercial aircraft such as the Airbus A350 and the Boeing 787, together with military aircraft such as the Lockheed Martin F35, with a large share of composite components of up to 50%, make it necessary for attention to be focussed on the development of new and effective maintenance strategies. In this paper, we address the development of ultrasonic measurement techniques, with a focus on structural health monitoring (SHM) techniques that are able to quickly inspect large structural parts of the aircraft. The combination of real-time SHM techniques, together with the parallel development of automated repair techniques for bonded structures, will make it possible to operate the aircraft at lower costs and for longer periods of time, thereby increasing the economic life of these aircraft structures.

1 INTRODUCTION

In the past three decades composite materials have gained an increased popularity, especially within the aerospace sector [1]. In this time-frame, rapid innovation has moved slowly away from the aerospace industry towards other sectors such as the information technology, photonics and renewable energy, while aerospace innovation slowed down in relative terms. Nowadays these sectors are even surpassing the aerospace industry in the novel use of composite materials, with examples such as large composite wind turbines, high value automotive products and composite bridges in the civil engineering sector. One of the factors in this change of focus, is the strict policy in civil aviation regarding certification of materials, techniques, systems and procedures. However, once certification of new materials and systems have been achieved, this certification requirement can also drive innovation in maintenance, repair and operations.

One of the main technological bottlenecks for the use of composite materials in aviation, is that new techniques and procedures are required for maintenance, repair and overhaul. The introduction of composite components in the A330/340, A380, Boeing 777 and composite primary structures in the Boeing 787, A350 and F35 has not led to a similar growth in the use of composites in repairs. Currently the repair of composite parts is either prohibited, leading to an extensive replacement program, labour intensive and therefore expensive, time consuming or executed with traditional metal materials, such as aluminium or titanium.

Carbon and glass fibre reinforced polymers thermoset and thermoplastic polymers are light in weight, they show an increased strength/weight ratio in comparison to conventional materials and a reduced sensitivity to corrosion and fatigue. A downside is their brittle behaviour and susceptibility to impact damage. One of the limiting factors for widespread use of composite materials in repairs is accurate and reliable localization of damage. When this damage occurs it is often difficult to identify as it either affects

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the reverse side of the material or causes internal delaminations. In particular the anisotropy of the material causes problems for conventional NDT detection techniques. Advances in non-destructive testing (NDT) techniques [2], such as the use of phased-array ultrasonics, optical NDT methods and acoustic cameras provide a partial solution, but they are expensive and labour intensive compared with the potential of structural health monitoring techniques, such as acoustic emission, Lamb wave ultrasonics and fibre-optic sensors [3].

A fast and efficient detection method for detecting barely visible damages on large surfaces would significantly advance the adoption of composites inn aerospace structures. This lack of appropriate detection techniques is also a limiting factor for other industries and could be used by a large community and bring the aerospace sector one step ahead.

In the current study we investigate a variety of structural monitoring techniques, which make it possible to inspect large surface areas within a short time frame, either for on-demand inspection, during maintenance or for continuous monitoring. The combination of an effective, real-time monitoring technique combined with currently developing automated repair techniques, will make it possible to perform the aircraft operations at a lower cost, for longer periods of time, thereby increasing the economic life of these aircraft structures.

2 CURRENT MONITORING TECHNIQUES

2.1 Ultrasonic wave propagation techniques

When considering mechanical vibrations, Doppler effects and ultrasonic wave propagation, as shown in figure 1, it is noted that besides the frequency, also the geometry of the material influences the analysis technique. When the wavelength of the signal is larger than the investigated geometry, or parts of the geometry, a modal analysis will be performed. The occurrence of damage can be detected using this technique [4] as well as an estimate of the location of damage. Ultrasonic techniques, which operate at higher frequencies are able to visualize a detailed internal picture are able to locate damage more

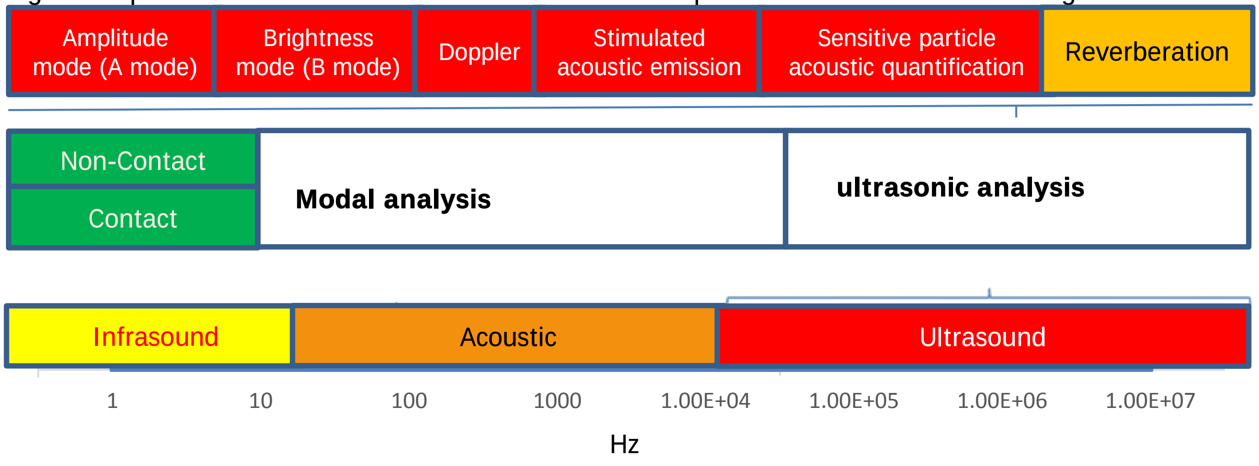


Figure 1. *Mechanical frequency spectrum, modal and ultrasonic material analysis, for contact and non-contact testing methods [6]. A large variety of ultrasonic detection methods have been developed [7].*

precisely, however in this increased frequency range, more signal attenuation occurs and datastreams become larger, providing challenges for the signal processing. Applying these signal processing techniques to the obtained ultrasonic signal, see figure 2, is another essential factor in deriving a reliable picture of the monitored material [5]. A large variety of signal processing techniques exist, whereby each method has its own advantages and disadvantages, depending on the type of material, the geometry and type of damage. Typical approaches are time of arrival of the first wavepacket and correlation techniques. In this paper the focus is on ultrasonic wave reverberation, which is the use of information contained within the later wavepackets as the primary source of information. By using this novel approach, it is possible to estimate the location where damage has occurred, within a short time frame.

Considering the type of ultrasonic wave that propagates in the structure is essential for detecting a specific type of damage for a certain material and geometry. For thick materials, shear and compressional wave are dominant within the material, and Stonely waves and Rayleigh waves are important at the boundaries of the investigated material. When the considered material is plate like, with thickness comparable to or smaller than the ultrasonic wavelength $(\frac{d}{\lambda} < 1)$, then Lamb waves start to occur. Especially for aerospace structures, the Lamb wave can be useful to investigate large surfaces with relatively low frequencies which are well below 1 MHz.

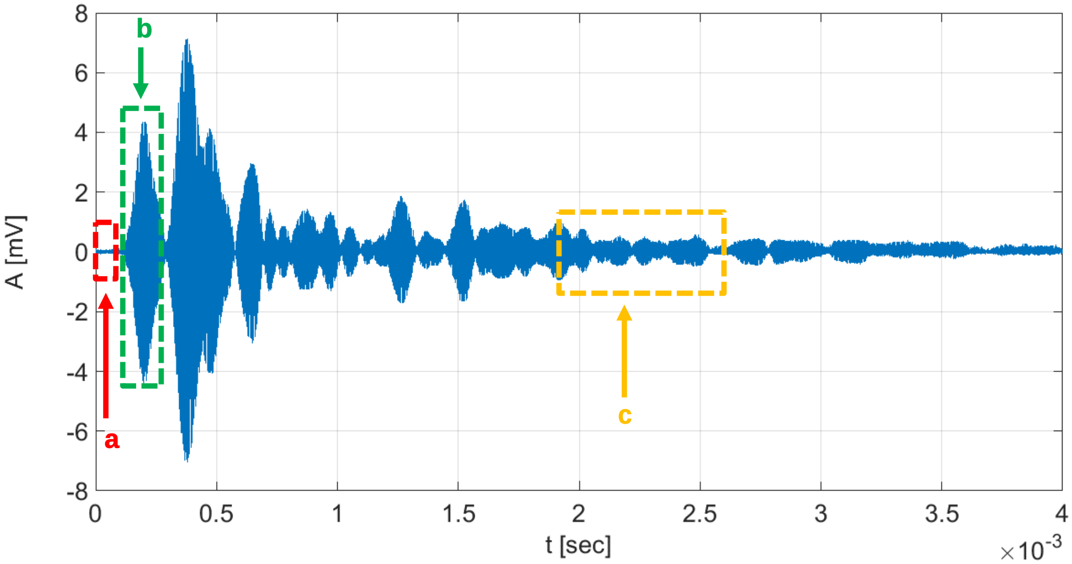
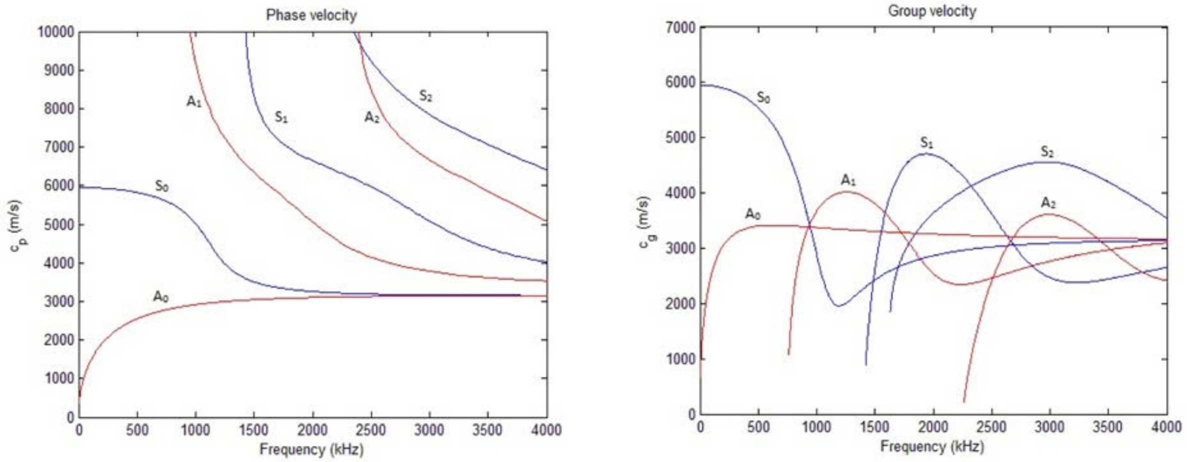


Figure 2. *Ultrasonic time trace, from an input Gaussian pulse, showing amplitude as a function of time. Several characteristic areas can be recognized in the graph: a) trace signal due to background noise, b) first arrival of the transmitted Gaussian pulse, and c) reverberated response signal, where due to multiple reflections, the signal becomes chaotic and is attenuated [8]*

The underlying physical principle of Lamb wave ultrasonics is that the ultrasonic wave is modified by defects and damages in the structure and that these changes in the wave pattern are detected by the signal processing. The ultrasonic wave is generated by the excitation of a piezoelectric transducer. The propagating wave is received by another transducer, which will register the surface waves at its location. For ultrasonic waves in the hundreds of kHz frequency range, Lamb waves are generated in plate-like structures. These waves have symmetric (S) and asymmetric (A) propagation modes, see figure 3, which can be used to advantage in the monitoring. Their wave behaviour makes them sensitive to either surface effects, such as surface damage, or internal changes such as delamination, making it possible to detect different types of damages. At these low frequencies, the ultrasonic Lamb waves attenuate much less than the more conventionally applied MHz high-frequency waves used in NDT, allowing large areas to be investigated with Lamb waves. The described method compares favourably to current thickness, flaw and bond test ultrasonic test equipment. This new approach could also work on aluminium alloy materials (and other traditional materials), and simplify the maintenance of conventional aircraft [7].



(a) (b)

Figure 3. Phase velocity (a) and group velocity (b) dispersion curves for an isotropic material with $c_L \approx$ 7200 m/s, $c_T \approx$ 3370 m/s, and a thickness of $d \approx$ 2.2 mm [9].

In this study the focus is on investigating whether the physical principle of repeated reverberating signals allows the development of a fast, efficient detection method for barely visible impact damage (BVID) on large surfaces. This method is based on detecting changes in the material using Lamb waves [9]. After performing a reference measurement on an undamaged material, a second measurement of the same material is made at the same location and a comparison of the signals should show that they are similar. However, when damage occurs the signal will change. The method is not based on the analysis of the first arrival or a specific alteration in phase or time, but rather considers the entire reverberation of the signal. By analysing the cross correlation comparison of both reverberation signals, together with the autocorrelation function of the original signal, it is possible to distinguish changes in the occurring wave pattern over very large areas with a minimal number of sensors.

In the past decade the reverberation technique was investigated for detecting damage in concrete structures [10]. Instead of analysing the full wave equation, a simplified diffusion equation was considered

$$\frac{\partial}{\partial t}G(\bar{r},\bar{r}_0)+\frac{1}{\tau_i}G(\bar{r},\bar{r}_0)-D\Delta G(\bar{r},\bar{r}_0)=\delta(\bar{r}-\bar{r}_0)\delta(t), \qquad (1)$$

Where $G(\bar{r},\bar{r}_0)$ is a Green's function, τ_i is the absorption time, D a diffusion constant and δ the point source Dirac function [10].

The ultrasonic verification method has been investigated with bonded PZTs [11] and air-coupled transducers [12]. By testing samples under different environmental conditions, a varying working environment can be mimicked. In the current set-up the number of transducers is minimized to two sensors. However, when use is made of more transducers, it is already possible to make a simplified surface mapping of the investigated object, which makes the data analysis afterwards far easier. In contrast to other methods the number of sensors for a tomographic approach is reduced. Due to the enhanced 2D images generated by this approach, the operator needs a much lower entry level to use the equipment and is able to perform a much more detailed analysis in a fraction of the time.

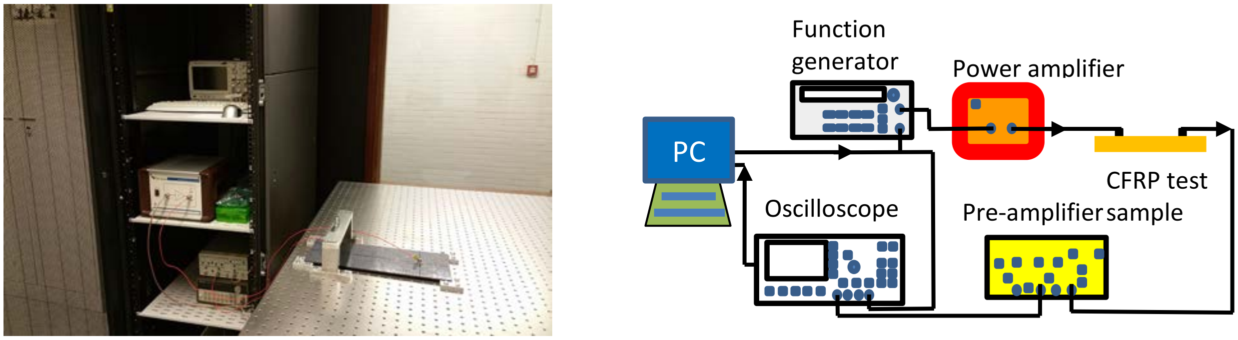


Figure 4 *a) Ultrasonic verification setup with composite specimen mounted on the optical table. b) Schematic description of the ultrasonic verification equipment.*

The techniques shown in figure 4 will be developed further to attain Technical Readiness Level (TRL) 4 within the next couple of years, to show the feasibility and to attract additional industry investment for further development. For example the setup will be expanded to include multiple sensors. It is envisaged that the described techniques will first be used for maintenance purposes, after certification. Over time, the development of new and implementation of onboard Structural Health Monitoring systems techniques will influence both the design of new aircraft and the development of new maintenance procedures.

2.2 Structural health monitoring

Current airframe monitoring is mainly based on manual non-destructive inspection methods [13]. Automated continuous monitoring techniques are under development in a variety of disciplines, ranging from bridges and dams in the civil engineering sector [14], skyscrapers, buildings in earthquake sensitive areas, the mining industry, the energy & processing sector and transport [15]. An increased demand for safety, for most of the above mentioned sectors, is demanded by regulators all over the world. This demand combined with the extended life expectancy of civil engineering and transport structures as well as the miniaturization of sensors has caused a necessity to make a parallel development of structural health monitoring systems for all above mentioned branches.

A maintenance-based structural health monitoring technique, consisting of a small set of multi-functional sensors, could in the next phase of the research programme, become a diagnostic and prognostic tool. Real-time data logging over long periods of time gives the possibility to apply data-mining techniques, similar to those employed for engine data monitoring systems. These may show defects that remain hidden during conventional NDT inspections. A third development stage would be the development of an inflight Structural Health Monitoring system as shown in figure 5, which will give the pilot ‘structural awareness’ (similar to the human nervous system) of the airframe structure, allowing the pilot to take preventative action to prevent additional structural damage. Fleet life cycle management, is considered for the next generation of military aircraft [13] as well for commercial aircraft, such as the Airbus A350 and Boeing 787. The certification of these modern aircraft for life expectancies of 30 years and beyond [16] as well as the small profit margins within the airline industry, forcing airlines to optimize their maintenance strategies

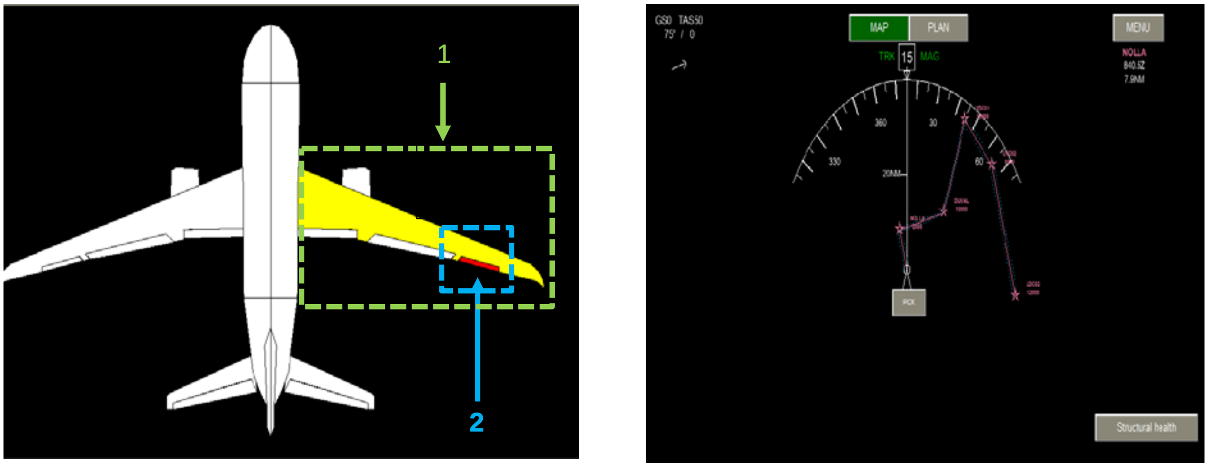


Figure 5. *a) Example of how inflight structural health monitoring could be combined with visualisation tools. Region 1 is a warning indication of medium damage to wing and region 2 indicates large structural damage to the aileron. b) Example of a multi-functional display [17, 18] which would be used to present SHM data to the pilot, in combination with acoustic warning.*

2.3 Maintenance repair and overhaul 2.0

By visualizing the detected structural information, as described in section 2.2, the position of individual damaged regions and their influence on the entire structure would also be communicated to maintenance personal. A user friendly structural health monitoring systems could also be used by management and other non-specialized personal. Further this SHM information could be exported to existing CAD, FEM and CFD models (which are available after production of aircraft), to open the possibility of performing much more case specific repairs. This could, for example, make it possible to minimize the area required for repair. In combination with automated repair systems, which can perform generic tasks such as multi-axial positioning using robotic arms [19], SHM data could be used to accelerate repair procedures. Robotic systems can either be locally stationary systems, such as a robotic arm, or a movable system, which can move along the surface of the aircraft and locate itself temporarily at a specific spot. The latter would have a movement capability similar to a Gecko, which is able to climb vertical walls. The removal of the material can be performed with the latest generation of CNC equipment, which remove a minimal amount of material and take into account the anisotropy as well as the layering of the composite material, together with heating effect on the glue and materials involved.

In the further processing step, material can be added, layer by layer, with the optimal amount of glue within a minimal time frame. Also 3d printing techniques could be applied. Real time monitoring of the repair procedure and minimizing the quality variation between each procedure also become possible. Especially for uncommon sorts of damage, where not a lot of information from separate destructive tests is available, this additional capability could provide a benefit. Planning a maintenance repair procedure could, using the above described capabilities benefit significantly, give the management an additional tool to quantify the quality of a procedure, together with reducing the labour costs and turnaround time.

3 CONCLUSIONS

A wide variety of methods exist for detecting damage. In this paper an overview of the most commonly used methods was given. The focus has been on methods that can be performed within short time frames, e.g. the reverberation technique, and with a small amount of effort can give a good estimate of the damage location. This will in future be combined with the automation of repair procedures. Visualizing information from a structural health monitoring system will make it possible to increase safety during flight and to get more reliable statistical data regarding the reliability of structures. Maintenance organizations can use these new tools to locate damage more quickly, weigh the importance of each damage spot and to accelerate repair, thereby reducing both labour costs and turnaround time. After the repair procedure is completed the quality of the repair can immediately be determined by the SHM system as well.

Nomenclature

c_L = Longitudinal wave velocity
c_t = Shear wave velocity
D = Diffusion constant
d = Thickness of plate
G = Green function
$\bar{r}$ = Transducer location vector
$\bar{r}_o$ = Point source location vector
t = Time
δ = Point source Dirac function
λ = Wavelength
τ_i = Absorption time

4 REFERENCES

[1] Khan, R., "*Delamination Growth in Composites under Fatigue Loading*," Ph.D. Dissertation, Faculty of Aerospace Engineering, Delft University of Technology, Delft, 2013.

[2] Bos, M.J., Habets, G.M.H.J., "*Review of aeronautical fatigue investigations in the Netherlands during the period March 2013 - March 2015*", NLR-TP-2015-123, 2015

[3] van Tooren, M., Groves, R.M., "*White Paper on Structural Health Monitoring for Aircraft Structures*", Fokker, 2014.

[4] Grooteman F., "*Damage detection for a SHM system based on optical fibres applied to a composite fuselage panel*". SEICO13 of SAMPE Europe, 34th International Technical Conference & Forum Proc., 11th – 12th of March 2013, Paris, France, 2013.

[5] Ochôa, P., Groves, R.M., Benedictus, R., "*Lamb wave dispersion time-domain study using a combined signal processing approach*", Proc. 6th International Conference on Emerging Technologies in Non-Destructive Testing, Belgium, 2015.

[6] NDT Resouce center, "*Modes of sound wave propagation*", downloaded July 5th 2015, from https://www.nde-ed.org/EducationResources/CommunityCollege/Ultrasonics/Physics/ modepropagation.htm

[7] Reiser, M.F., Semmler, W., Hricak, H., "*Magnetic Resonance Tomography*", Springer, 1389, 2008.

[8] Sprik, R., de Boer, R.J., "*Method and system for non-destructive testing"*, NL Patent 2006345; (March 2011).

[9] Ochôa, P., Infante, V., Silva, J.M., Groves, R.M., "*Detection of multiple low-energy impact damage in composite plates using Lamb wave techniques*", Composites Part B, 2015.

[10] Larose, E., Planes, T., Rossetto, V., Margerin, L., "*Locating a small change in a multiple scattering environment*", Applied Physics Letters, Vol. 96, 204101, 2010.

[11] Pelt, M., Boer, R.J., Schoemaker, C., Sprik, R. "*Ultrasonic verification of composite structures*", Proc. In EWSHM-7th European Workshop on Structural Health Monitoring, 2014.

[12] Alleman, G., Pelt, M.M.J.M., Groves, R.M., "*Air-coupled ultrasound for damage detection in CFRP using Lamb waves and ultrasonic verification",* Proc. ICAST2014: 25nd International Conference on Adaptive Structures and Technologies, The Hague, 2014.

[13] Bos, M.J., Hwang, J.S., Grooteman, F.P., Dominicus, J.A.J.A., Park, C.Y., "*Load Monitoring and Structural Health Monitoring (SHM) within the Royal Netherlands Air Force*", NLR, 2014.

[14] Veerman, R.P., Miao, S., Koenders, E.A.B., Knobbe, A., "*Data-intensive structural health monitoring in the infrawatch project*", Structural health monitoring for infrastructure sustainability: Proc. 6th International Conference on Structural Health Monitoring of Intelligent Infrastructure SHMII-6, Hong-Kong (China), 2013.

[15] Neylon, S., Richardson, A., van Heeren, H., "*Expert Workshops in Microsystems for Structural Health Monitoring*," FP6 Nexus Plus, 2008.

[16] Giurgiutiu, V., Soutis, C., "*Enhanced Composites Integrity Through Structural Health Monitoring*", Appl. Compos. Mater., 2012.

[17] Jacobsen, A.R., "*787 Flight Deck Displays*", Boeing Commercial Airplanes, 2006.

[18] Ewald, V., Ochoa, P., Groves, R.M., Boller, C., "*Design of a Structural Health Monitoring System for a Damage Tolerance Fuselage Component*", to be presented at 7th International Symposium on NDT in Aerospace, Bremen, 2015.

[19] Marsh, G., "*The challenge of composite fuselage repair*", Reinforced Plastics, 2012.